The Atlantic Hurricane Database Re-analysis Project - Documentation for 1851-1910 Alterations and Additions to the HURDAT Database

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ABSTRACT

A re-analysis of the Atlantic basin tropical storm and hurricane database ("best track") for the period of 1851 to 1910 has been completed. This reworking and extension back in time of the main archive for tropical cyclones of the North Atlantic Ocean, Caribbean Sea and Gulf of Mexico was necessary to correct systematic and random errors and biases in the data as well as to incorporate the recent historical analyses by Partagas and Diaz. The re-analysis project provides the revised tropical storm and hurricane database, a metadata file detailing individual changes for each tropical cyclone, a "center fix" file of raw tropical cyclone observations, a collection of U.S. landfalling tropical storms and hurricanes, and comments from/replies to the National Hurricane Center's Best Track Change Committee. This chapter details the methodologies and references utilized for this re-analysis of the Atlantic tropical cyclone record.

1.) Introduction

This chapter provides documentation of the first efforts to re-analyze the National Hurricane Center's (NHC's) North Atlantic hurricane database (or HURDAT, also called “best tracks” since they are the “best” determination of track and intensity in a post-season analysis of the tropical cyclones). The original database of six-hourly tropical cyclone (i.e. tropical storms and hurricanes) positions and intensities was assembled in the 1960s in support of the Apollo space program to help provide statistical tropical cyclone track forecasting guidance (Jarvinen et al. 1984). Since its inception, this database, which is freely and easily accessible on the Internet from NHC's webpage <http://www.nhc.noaa.gov/pastall.shtml>, has been utilized for a wide variety of additional projects: setting of appropriate building codes for coastal zones, risk assessment for emergency managers, analysis of potential losses for insurance and business interests, intensity forecasting techniques, verification of official and model predictions of track and intensity, seasonal forecasting, and climatic change studies. Unfortunately, HURDAT was not designed with all of these uses in mind when it was first put together and not all of them may be appropriate, given its original motivation and limitations.

There are many reasons why a re-analysis of the HURDAT dataset was both needed and timely. HURDAT contained many systematic and random errors that needed correction (Neumann 1994). Additionally, as our understanding of tropical cyclones had developed, analysis techniques at NHC changed over the years, and led to biases in the historical database that had not been addressed (Landsea 1993). Another difficulty in applying the hurricane database to studies concerned with landfalling events was the lack of exact location, time and intensity information at landfall. Finally, recent efforts led by Jose Fernandez-Partagas to uncover previously undocumented historical tropical cyclones in the mid-1800s to early 1900s have greatly increased our knowledge of these past events (Partagas and Diaz 1996a), which also had not been incorporated into the HURDAT database.

Currently, the HURDAT database is updated at the end of each year's hurricane season after the NHC hurricane specialists perform a post-season analysis of that year's storms. The most recent documentation generally available for the database is a *NOAA Technical Memorandum* by Jarvinen et al. (1984). While this reference is still valid for most descriptions of the tropical cyclone database, it too is in need of revision. This chapter is designed to help provide a more up to date documentation for HURDAT.

A re-analysis of the Atlantic tropical cyclone database is justified by the need to address these deficiencies as well as to extend the historical record back in time. This chapter details the first efforts to improve both the accuracy and consistency of HURDAT for the years of 1886 to 1910 as well as to provide an additional thirty-five years (1851-1885) into the archived database of Atlantic tropical storms and hurricanes.

2.) Outline of Databases Provided in the Re-Analysis

As part of the re-analysis effort, five files have been made available:

1) The revised Atlantic HURDAT: This contains six-hourly intensity (maximum sustained 1-minute winds at the surface [10 m] and, when available, central pressures) and position (to the nearest 0.1° latitude and longitude) estimates of all known tropical storms and hurricanes.

2) A HURDAT metafile: This documentation file has detailed information about each change in the revised HURDAT. Included are the original HURDAT values of position and/or intensity, the revised values in HURDAT, and the reasoning behind the changes.

3) A “center fix” file: A file has been created that is composed of raw observations of tropical cyclone positions (thus “center fixes”) and intensity measurements from either ships or coastal stations.

4) A U.S. landfalling tropical storm and hurricane database: This file contains information on the exact time, location, intensity, radius of maximum winds (RMW), environmental sea level pressure and storm surge for continental U.S. landfalling (and those whose centers do not make landfall, but do impact land) tropical storms and hurricanes.

5) NHC Best Track Change Committee comments: This file provides detailed comments from the NHC’s Best Track Change Committee – a group tasked with approving alterations to the HURDAT database. Replies by the authors to the various comments and recommendations are also included.

These files along with track maps showing all tropical storms and hurricanes for individual years are available on the HURDAT re-analysis web page: <http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html>.

3a.) The Work of Jose Fernandez-Partagas

Efforts to digitize and quality control the work of Partagas and Diaz (1995a, 1995b, 1996a, 1996b, 1996c, 1997, 1999) produced the largest additions and alterations to HURDAT. Partagas and Diaz utilized a variety of sources for their research: ship reports in newspapers, individual and seasonal summaries published in the *Monthly Weather Review*, documents from government agencies, historical reviews and scientific publications (Table 1). A distillation of this information by the re-analysis project led to the creation of completely new tropical cyclone tracks and intensities for the years 1851 to 1885 and the alteration of existing track and intensity data for the period of 1886 to 1910. Secondarily, the re-analysis effort also corrected many of the existing systematic and random errors that existed in the 1886 to 1910 portion of HURDAT. The improvements included: a) corrected interpolations of winds near landfall, b) more realistic speed changes at the beginning and/or end of the tropical cyclone track, c) improved landfall locations, and d) corrected of reduction of inland winds using Kaplan and DeMaria's (1995, 2001) methodology. A number of sources beyond those utilized by Partagas and Diaz were also used in the re-analysis work, which are detailed in Table 1.

Jose Fernandez-Partagas' research - extremely painstaking and time-consuming work - was detailed in full in the volumes from Partagas and Diaz (1995a, 1995b, 1996b, 1996c, 1997 and 1999). An example of the documentation that he provided is shown below for the first storm of 1856. (The storm track mentioned in Fig. [1] is shown as Storm 1 in Figure 1.)

> "Storm 1, 1856 (Aug. 10-11).
>
> Tannehill (1938) has mentioned this storm as having occurred along the Louisiana coast. Dunn and Miller (1960) and Ludlum (1963) have also mentioned this storm. The author of this study has prepared the storm track which is displayed in Fig. [1].
>
> The New-York Daily Times, Aug. 16, 1856 p.1, col.1, published that there had been a storm in the New Orleans area on August 10 and that such a storm had been most disastrous at Last Island (Ile Derniere). A narrative of what had happened at Last Island included some meteorological remarks: Heavy N.E. winds prevailed during the night of August 9 and a perfect hurricane started blowing around 10 A.M. August 10. The water commenced to rise about 2 P.M. and by 4 P.M. currents from the Gulf and the Bay had met and the sea waved over the whole island (The New-York Daily Times, Aug. 21, p.3, col.4).
>
> The following information has been extracted from Ludlum (1963): The ship "C. D. Mervin" passed through the eye of the storm off the Southwest Pass. Captain Mervin checked the barometer at 8 A.M. Aug. 10 and noticed a reading of 28.20 inches, a 24-hr drop of 1.70 inches. At 9 A.M. the ship had a calm which lasted for 5 minutes. The sun shone and there was every appearance of clearing off but the wind suddenly struck the ship from the opposite direction. For two more hours, more a southerly hurricane struck the ship and then gradually abated. After the hurricane, the ship location was found to be only 60 miles to the W.S.W. of Southwest Pass.
>
> At Iberville, Parish of Vermillon, the Aug. 10-11 storm raged with terrific force but only gales were reported at New Orleans, where the maximum wind at observation time was force 8 on the Beaufort scale (39-46 miles per hour) from an easterly direction at 2 P.M. August 10 (Ludlum, 1963).
>
> It can be inferred from the above information that Storm 1, 1856 was a hurricane which was moving on a northwesterly course as shown in Fig. [1]."

3b.) Center Fix Files

From the observations uncovered by Partagas for this storm – Storm 1, 1856, the following "center fix" data were archived as shown in Table 2a. (A center fix position observation was unavailable for this storm, so a sample data point for Storm 5, 1852 is shown as an example in Table 2b.)

The conversion from descriptive measures of winds to quantitative wind speeds, while quite subjective, is assisted by the usage of the Beaufort Scale, which was developed as a wind force scale for sailing ships by Admiral Francis Beaufort in 1805 and made mandatory for log entries in the British Royal Navy by 1838 (Kinsman 1969). Subsequently, the scale evolved into one associated with specific wind speed ranges as specified by interpretations of the sea state, rather than the wind's impact on sails (Table 3). Due to limitations at the top end of the Beaufort Scale, the center fix and best track data in the re-analysis generally list ship reports of "hurricane" force winds as 70 kt (36 m s^{-1}) winds. The listed wind speeds were boosted to 90 kt (46 m s^{-1}) when ship reports included terms such as "severe", "violent", "terrific", or "great hurricane". Hurricanes at sea were not assigned a best track intensity value of major hurricane (Saffir-Simpson Scale Category 3, 4 or 5; 96 kt [50 m s^{-1}] or greater maximum sustained surface wind speeds) unless corresponding central pressure data was able to confirm such an intensity. Caution was warranted in the direct use of these Beaufort Scale wind estimates for tropical storm and hurricane intensity assignments due to lack of consistency and standardization in the scale during the late 19th and early 20th Centuries (Cardone et al. 1990). However, in many cases these Beaufort Scale measurements by mariners were the only clues available for estimating the intensity of tropical cyclones of this era.

Occasionally, there were ship observations with no specific dates available. These were primarily utilized to provide information about the track of the storm (e.g. a southwest gale noted by a ship captain would indicate a tropical cyclone located to the northwest of the ship's position) as long as other ship/land observations could help pinpoint its timing. "Dateless" ship observations were also infrequently utilized to assist in the intensity estimates.

For land based observations of wind speed, there were generally two types available during the second half of the 19th and early 20th Centuries: visual estimates and the four cup Robinson anemometer (Ludlum 1963, Ho 1989). Visual estimates, though crude, were somewhat standardized by use of a ten point scale for use by volunteers of the Smithsonian Institute as well as by Army observers at various forts (Table 4, M. Chenoweth, personal communication, 2001).

Of modestly more reliability was the four cup anemometer, first developed by Robinson in the 1840s (Kinsman 1969). Of primary difficulties were calibrating the instrument and its mechanical failure in high wind conditions. Even as late as 1890, the highest wind that could be reliably calibrated with this instrument was only about 30 kt (from a whirling machine), due to lack of a strict comparison with a known quantity of stronger winds (Fergusson and Covert 1924). By the early 1920s, wind tunnels allowed for calibration against much stronger winds. These showed that the winds from these early cup anemometers had a strong overestimation bias, which was most pronounced at very strong wind speeds (Fergusson and Covert 1924). For example, an indicated wind of minimal hurricane force (64 kt) in actuality was only about 50 kt. Moreover, most of these early four cup anemometers were disabled or destroyed before sampling the highest winds of hurricanes. The strongest observed winds in an Atlantic hurricane by this type of anemometer was a 5-min sustained wind measurement of 120 kt in storm 2, 1879, just before the instrument was destroyed by this North Carolina-landfalling hurricane (Kadel 1926). (A standard of 5-min was typically utilized in U.S. Army Corps and Weather Bureau reports of "maximum winds", due to instrumental uncertainties in obtained reliable values for shorter time period winds.) With reliable calibrations available in the 1920s, this extreme wind's true velocity was only about 91 kt. Current understanding of gustiness in hurricane conditions suggest a boost of 1.05 to convert from a 5-min to a 1-min maximum sustained wind (Dunion et al. 2002), giving a best estimate of the maximum 1-min sustained wind of about 96 kt.

Coastal station wind data listed in the center fix files are the original measurements provided. It is in the interpretation of these data for inclusion into the best track that these various biases and limitations (i.e., strong overestimation in high wind regime, conversion of 5-min to 1-min wind, and instrumental failure) are taken into account. More on the difficulties of the intensity estimations is found in the Limitations and Errors section

3c.) Wind-Pressure Relationships

Sea level atmospheric pressure measurements (either peripheral pressures or central pressures) can provide estimates of the maximum sustained wind speeds in a tropical cyclone, in the absence of in situ observations of the peak wind strength. In the case of Storm 1, 1856, the ship "C.D. Mervin" observed a peripheral pressure of 955 mb (Table 2a), likely while in the western eyewall. Central pressures of tropical cyclones can be estimated from such peripheral pressure measurements if relatively reliable values of the RMW and environmental (or surrounding) sea level pressure can also be obtained. Radius of maximum wind information was occasionally obtained from ships or coastal stations that were unfortunate enough to have the eye of the hurricane pass directly overhead. Careful notation of the times of the peak winds and the calm of the eye experienced along with the best estimate of the translational speed of the hurricane allowed for direct calculation of the RMW. Another method for estimating RMW was to measure the mean distance from the hurricane's track to the location of the peak storm surge and/or peak wind-caused damages. Such RMW measurements or estimates were relatively rare over the open ocean and only somewhat more common as hurricanes made landfall over populated coastlines. Central pressure can then be estimated from the following equation (Schloemer, 1954; Ho, 1989):

$$\frac{P_R - P_o}{P_n - P_o} = e^{(-RMW/R)}$$

where P_R is the sea level pressure at radius R, P_o is the central pressure at sea level, and P_n is the environmental (or surrounding) sea level pressure at the outer limit of a tropical cyclone where the cyclonic circulation ends.

Once a central pressure has been estimated, maximum sustained wind speeds can be obtained from a wind-pressure relationship. The current standard wind-pressure relationship for use in the Atlantic basin by NHC (OFCM 2001) is that developed by Dvorak (1984) as modified from earlier work by Kraft (1961).

The re-analysis developed new wind-pressure relationships (described below) to help derive winds from an observed (or estimated) central pressure only in the absence of reliable wind data. These relationships are not intended to give best track wind estimates for hurricanes in the last few decades of the 20th Century. During this time, accurate flight-level wind measurements were commonly available from reconnaissance aircraft. The new wind-pressure relationship estimates should not supercede the use of any reliable, direct wind observations (rare in the 19th and early 20th centuries), which may be available in a tropical cyclone. It is important to avoid situations where accurate in situ data are modified by estimates from a wind-pressure relationship.

The re-analysis used new wind-pressure relationships for four regions in the Atlantic basin: Gulf of Mexico (GMEX), southern latitudes (south of 25°N), subtropical latitudes (25-35°N) and northern latitudes (35-45°N). Regional wind-pressure relationships were developed because of a tendency for the association to differ depending upon latitude. The equations relating maximum sustained surface wind speeds to a corresponding central pressure as well as those for the Kraft and Dvorak formulations are shown below and representative values are displayed in Table 5. The tabular wind values are based on the following regression equations:

1) For GMEX   Wind (kt)=10.627*(1013-P_o)$^{0.5640}$ Sample size =664; r=0.991

2) For < 25°N   Wind (kt)=12.016*(1013-P_o)$^{0.5337}$ Sample size =1033; r=0.994

3) For 25-35°N   Wind (kt)=14.172*(1013-P_o)$^{0.4778}$ Sample size =922; r=0.996

4) For 35-45°N   Wind (kt)=16.086*(1013-P_o)$^{0.4333}$ Sample size =492; r=0.974

5) For Kraft   Wind (kt)=14.000*(1013-P_o)$^{0.5000}$ Sample size =13

The central pressure for these equations is given in units of millibars and r refers to the linear correlation coefficient. Dashes in Table 5 indicate that the pressure is lower than that available in the developmental dataset. Wind and pressure data used for the regression were obtained from the HURDAT file, 1970-1997. The developmental dataset excludes all overland tropical cyclone positions. Data for the < 25°N zone were obtained from longitudes of 62°W and westward. Data for the 25-35°N zone are from 57.5°W and westward. Data for 35-45°N include the longitudes of 51°W and westward. GMEX includes all over-water data west of a line from northeastern Yucatan to 25°N, 80°W. These locations were chosen based on their accessibility by aircraft reconnaissance that can provide both actual wind speed and pressure measurements.

When developing the wind-pressure relationships, attempts were first made to develop the equations with all of the available data for each region. However, the overwhelming numbers of observations at the low wind speed ranges overweighted the observations of the tropical storms and Category 1 hurricanes at the expense of the major hurricanes. When the derived equations were compared against the observations of wind and pressure at the very high wind values (> 100 kt [51 m s^{-1}]), the fit was quite poor. This was overcome by binning the observations into 5 mb groups and then performing the regression. Using this methodology, the observations at the 981-985 mb range, for example, were weighted equally to those of the 931-935 mb range. After performing the regression this way, a much more accurate set of regression equations with the wind and pressure estimates for the Category 3, 4 and 5 hurricane ranges was obtained. Because this method reduces the standard deviation of the sample as well as the sample size, the correlation coefficients are inflated.

In general, the Dvorak formulation is most similar to the Gulf of Mexico and southern latitude relationships. For example, a 960 mb hurricane is suggested to have 102 kt (52 m s^{-1}) sustained surface winds from Dvorak's relationship, which is quite close to the 100 kt (51 m s^{-1}) estimate provided by both the Gulf of Mexico and southern latitude relationships. However, there is a tendency for the Dvorak wind values to be higher than winds provided by the Gulf of Mexico and southern latitude wind-pressure relationships for the extremely intense (< 920 mb) hurricanes, though the number of data points available for calibration of this end of the wind-pressure curves is quite low. In addition, the Dvorak wind-pressure relationship systematically overestimates the wind speeds actually utilized by NHC for the subtropical and northern latitude hurricanes with central pressures less than 975 mb. For the case of a hurricane with a 960 mb central pressure, the subtropical and northern latitude equations suggest 94 kt (48 m s^{-1}) and 90 kt (46 m s^{-1}), respectively. The weaker winds in higher latitudes can be explained physically with the following reasoning: As hurricanes move poleward encountering cooler sea surface temperatures and begin to evolve into an extratropical cyclone, the tight pressure gradient and resulting wind field typically weakens and expands outward. This is due in part to structural evolution, but also due to less efficient vertical momentum transport by convection in a more stable environment. In addition, increases in the Coriolis force causes a corresponding, but small, decrease in tangential wind speed (Holland 1987). Since these changes become more pronounced as the tropical cyclones move into higher latitudes, an even larger reduction in wind speed was utilized poleward of 45^{o}N. It is thus consistent that the Dvorak wind-pressure relationship overestimates of winds in higher latitudes because the original formulation of Kraft is based primarily upon observations from the Caribbean Sea and Gulf of Mexico.

The use of wind-pressure relationships to estimate winds in tropical cyclones has a few associated caveats. First, for a given central pressure, a smaller-sized tropical cyclone (measured either by RMW or radius of hurricane/gale force winds) will produce stronger winds than a large tropical cyclone. From Vickery et al. (2001), the mean RMW (in km) of Atlantic tropical cyclones can be expressed as a function of central pressure (P_o), environmental pressure (P_n) and latitude (L):

$$\ln(RMW) = 2.636 - 0.00005086*(P_o - P_n)^2 + 0.0394899*(L).$$

Tropical storms and hurricanes with observed/estimated RMW that deviated by 25-50% from the average RMW values had wind speeds adjusted accordingly by about 5 kt. Tropical cyclones with RMW dramatically (more than 50%) different from climatology had winds adjusted by about 10 kt.

A second caveat concerns the translational speed of the tropical cyclone. In general, the translational speed is an additive factor on the right side of the storm and a negative factor on the left (Callaghan and Smith 1998). For example, a tropical cyclone moving westward in the Northern Hemisphere at 10 kt (5 m s^{-1}) with maximum sustained winds of 90 kt (46 m s^{-1}) on the west and east sides would produce approximately 100 kt (51 m s^{-1}) of wind on the north side and only 80 kt (41 m s^{-1}) on the south side. At low to medium translational speeds (less than around 20 kt [10 m s^{-1}]), the variation in storm winds on opposite sides of the storm track is approximately twice the translational velocity, although there is substantial uncertainty and non-uniformity regarding this impact on tropical cyclone winds. At faster translational speeds, this factor is somewhat less than two (Boose et al. 2001). Storms that move significantly faster than the regionally-dependent climatological translational speeds (Neumann 1993, Vickery et al. 2001) have been chosen in the re-analysis to have higher maximum sustained wind speeds than slower storms with the same central pressure. Similarly, storms with slower than usual rates of translational velocity may have slightly lower winds for a given central pressure. Such alterations to the standard wind-pressure relationship were previously accounted for to some degree in the original version of HURDAT (Jarvinen et al. 1984), so the period of 1886 to 1910 was checked for consistency in the implementation of translational velocity impacts upon maximum sustained surface winds and changes made where needed.

A third caveat of the wind-pressure relationships is that these algorithms were derived assuming over-water conditions. The use of the relationship for tropical cyclones overland must consider the increased roughness length of typical land surfaces and the dampening of the maximum sustained wind speeds that result. In general, maximum sustained wind speeds over open terrain exposures (with roughness lengths of 0.03 m) are about 5-10% slower than over-water wind speeds (Powell and Houston 1996), though for rougher terrain the wind speed decrease is substantially greater.

Finally, the derivation of the new regional wind-pressure relationships here is quite different from those originally analyzed by Kraft (1961) and Dvorak (1984). In these earlier efforts, observed central pressures were directly matched with observed maximum sustained surface winds.

One substantial limitation in such efforts was in obtaining a sizable sample upon which to derive the wind-pressure equations. Here this limitation is avoided by using the actual HURDAT wind and central pressure values in recent years, which does provide a large dataset to work with. However, this approach lacks a degree of independence, as NHC used the Kraft and Dvorak wind-pressure curves to provide estimates of maximum sustained surface winds from observed central pressures. This was especially the case during the 1970s, when aircraft flight-level winds were often discarded in favor of using the measured central pressure since there was considerable uncertainty as to how to extrapolate flight-level winds to the surface (Paul Hebert, personal communication). Such interdependence between recent HURDAT winds and central pressures may somewhat account for the close match between the Dvorak formulation to the Gulf of Mexico and southern latitude relationships. Despite these concerns, the development of regionalized wind-pressure relationships represents a step toward more realistic wind-pressure associations, though improvements beyond what has been presented here could certainly be achieved.

For many late 19th and early 20th Century storms, the central pressure could not be estimated from peripheral pressure measurements with the Schloemer equation because of unknown values for the RMW. Such peripheral pressure data were noted accordingly in the metadata file and used as a minimum estimate of what the best track winds were at the time. In most of these cases, the best track winds that were chosen were substantially higher than that suggested by the wind-pressure relationship itself. For Storm 1, 1856, maximum sustained winds consistent with the ship report of a 955 mb peripheral pressure measurement should be at least 105 kt (54 m s^{-1}) based on the Gulf of Mexico wind-pressure relationship (Table 5). In this case, 130 kt (67 m s^{-1}) was chosen for the best track at the time of this ship report (see Metadata Files section for more details).

3d.) Best Track Files

Tropical cyclone positions and intensities in HURDAT have been added to and changed for the re-analyzed period of 1851 to 1910. Tracks added for the years of 1851 to 1870 were digitized from the work of Partagas and Diaz (1995a). For the years 1871 to 1885, tracks for tropical cyclones that were unaltered by Partagas and Diaz (1995b, 1996b) were digitized directly from Neumann et al. (1993). The intensity estimates for 1851 to 1885 were determined with consideration of available raw data found in Partagas and Diaz (1995a, 1995b, 1996b), Ludlum (1963), Ho (1989) and other references, all of which have been recorded in the center fix files. A large majority of the tropical cyclones for the years 1886 to 1910 were altered in their track and/or intensity based upon the work of Partagas and Diaz (1996b, 1996c, 1997, 1999) and others listed in Table 1. Additions and changes made to individual tropical cyclones and the references that were the basis for the alterations are listed in detail in the metafiles for the separate tropical cyclones.

Tropical cyclone positions were determined primarily by wind direction observations from ships and coastal stations and secondarily by sea level pressure measurements and reports of damages from winds, storm tides or fresh-water flooding. Figure 2 illustrates for an idealized case how to estimate a tropical cyclone center from two ship observations. With these observations and the knowledge that the flow in a tropical cyclone is relatively symmetric (i.e. circular flow with an inflow angle of 20^{o}, Jelesnianski 1993), a relatively reliable estimate of the center of the storm can be obtained from a few peripheral wind direction measurements. However, analysis of tropical cyclone intensity is much less straightforward. Intensity, described as the maximum sustained 1-min surface (10 m) winds, of tropical cyclones for the period of 1851 to 1910 was based upon (in decreasing order of weighting) central pressure observations, wind observations from anemometers, Beaufort wind estimates, peripheral pressure measurements, wind-caused damages along the coast and storm tide. The next section in the chapter goes into detail about limitations and possible errors in the HURDAT position and intensity estimates for this era.

Table 6 provides the best track for Storm 1, 1856 based upon the Partagas and Diaz (1995a) track after conducting a critical independent assessment of their proposed positions and wind speeds (10 kt [5 m s^{-1}] increments) from known ship and land observations. This storm is a typical (though intense) example of one of the many newly archived tropical cyclones in the database. It is fully acknowledged that the best tracks drawn for tropical cyclones during the period 1851-1910 represent just a fragmentary record of what truly occurred over the open Atlantic Ocean. For this particular hurricane, the first six-hourly intensity given on 9 August at 00 UTC is 70 kt (36 m s^{-1}). It should not be inferred that this hurricane began its lifecycle at 70 kt, but instead that data were lacking to make an estimate of its position and intensity before this date.

Occasionally, there are tropical cyclones in the best track for which only one six-hourly position and intensity estimate was available (the “single point” storms - e.g. Storm 1, 1851). This was typically due to one encounter of a tropical cyclone by a ship or the landfall of the system along the coast with no prior recorded contact with other ships or coastal communities. The position and intensity estimated for such tropical cyclones have more uncertainty than usual, since it was not possible to check for consistency between consecutive position/intensity estimates. Users are to be cautioned that these single point storms will cause programming difficulties for versions of programs that are expecting at least two position/intensity estimates.

For the period of 1886 to 1930, the existing HURDAT was originally created from a once daily (12Z) estimate of position and intensity (Jarvinen et al. 1984). This caused some difficulty in situations of rapid intensification and rapid decay, such as the landfall of a tropical cyclone. For the latter case, the Kaplan and DeMaria (1995, 2001) models provided guidance for determining wind speeds for the best track after landfall of a tropical cyclone, but only in the absence of observed inland winds. The models used by Kaplan and DeMaria begin with a maximum sustained wind at landfall and provides decayed wind speed values out to about two days after landfall. Kaplan and DeMaria (1995) was designed for landfalling tropical cyclones over the southeastern United States where nearly all of the region within 150 nmi (275 km) of the coast has elevations less than 650 ft (200 m). Therefore the decay of winds over higher terrain areas such as Hispanola and much of Mexico predicted with the Kaplan and DeMaria (1985) model is inadequate (e.g., Bender et al. 1985). For these cases, a faster rate of decay than that given from this model (on the order of 30% accelerated rate of decay) was utilized in the re-analysis.

Ho et al. (1987) also developed several relationships for the decay of tropical cyclone central pressure after landfall, which were stratified by geographic location and value of the pressure deficit (environmental pressure minus central pressure) at landfall. In general, for tropical cyclones striking the U.S. Gulf Coast, at ten hours after landfall, the pressure deficit decreased by half. For Florida (south of 29°N) hurricanes at ten hours after landfall, the pressure deficit decreased by only one-quarter. For U.S. hurricanes making landfall north of Georgia, the pressure deficit is 0.55 times that of the landfalling value at ten hours after landfall. For extremely intense hurricanes, the rate of decay is somewhat faster. The relationships that Ho et al. (1987) developed are utilized here on occasion to derive an estimated central pressure at landfall from an inland central pressure measurement. The only deviation is for hurricanes traversing the marshes of southern Louisiana. In the Ho et al. (1987) study, Hurricane Betsy behaved anomalously, since it decayed much more slowly than most of the hurricanes striking the southeast U.S. It is hypothesized that this is due to enhanced sensible and latent heat fluxes available over the Louisiana marshes, relative to the dry land found throughout the rest of the region. Ho (1989) suggests utilizing the Florida decay rate for these hurricanes (e.g. Storm 10, 1893), since this rate better matches decay rates for hurricanes similar to Betsy.

The best track files for 1851 to 1870 do not include the tropical depression stages of tropical cyclones. Obtaining adequate information to document a storm's beginning and ending tropical depression stages would be extremely difficult, as most of the available observations focus upon gale force and stronger wind speeds. Additionally, motivation for this work was to better document the tropical storm and hurricane stages, as these account for the large majority of impacts on society (ie. winds, storm surge and inland flooding). However, the authors were able to add into HURDAT for the years 1871 to 1898 the dissipating tropical depression stage for those tropical cyclones that decayed over land. The Kaplan and DeMaria (1995, 2001) inland decay models were utilized to calculate wind speed estimates after landfall, in the absence of in situ wind or pressure data. This was done to ensure that existing tracks indicated by Neumann et al. (1993, 1999) and the original HURDAT were not truncated because the tropical cyclones decayed from tropical storm to tropical depression status. Starting in 1886, both the formative tropical depression stage and the tropical depression stage of tropical cyclones as they are decaying over water are included when available observations allow for a reasonable analysis. This is consistent with the previous HURDAT methodology. Additionally, where possible, the transition to the extratropical storm stage was documented and included in the best track.

The period of 1886 to 1898 in the existing HURDAT contained rather generic peak intensities: most systems that were determined to have been tropical storms were assigned peak winds of 50 kt (26 m s^{-1}) and most hurricanes were assigned peak winds of 85 kt (44m s^{-1}) (Hebert and McAdie 1997). In fact, of the 70 hurricanes from 1886 to 1898 in the original HURDAT, only one was Category 1, 59 were Category 2, 10 were Category 3 and none were Category 4 and 5.

This compares to recent historical averages of only about a fourth of all hurricanes are Category 2 (Pielke and Landsea 1998). In many of the tropical storms and hurricanes for this period, the available ship and land-based observations were utilized to provide a more realistic peak intensity value, if possible.

For the years 1899 to 1910, Partagas and Diaz (1996c, 1997, 1999) made extensive use of the Historical Weather Maps series, a reconstruction of daily surface Northern Hemispheric synoptic maps accomplished by the U.S. Navy and U.S. Weather Bureau in the late 1920s. This reconstruction effort was able to incorporate ship and coastal station data not available in the original tropical storm and hurricane track determinations. Thus, over 90% of the tracks for this twelve-year period have been modified.

3e.) Limitations and Errors:

The tropical storms and hurricanes that stayed out at sea for their duration and did not encounter ships (or tropical cyclones that sunk all ships that they overran) obviously will at this point remain undocumented for the time period of 1851 to 1910. It was estimated that the number of “missed” tropical storms and hurricanes for the 1851-85 era is on the order of 0-6 per year and on the order of 0-4 per year for the period of 1886 to 1910. (The higher detection for the latter period is due to increased ship traffic, larger populations along the coastlines and more meteorological measurements being taken.) By no means should the tropical cyclone record over the Atlantic Ocean be considered complete for either the frequency or intensity of tropical storms and hurricanes for the years 1851 to 1910. However, more accurate and complete information is available for landfalling tropical cyclones along much of the United States coastline. (See the U.S. landfalling tropical cyclone section for more details.)

Tropical storms and hurricanes that remained out over the Atlantic Ocean waters during 1851 to 1910 had relatively few chances to be observed and thus included into this database. This is because, unlike today, the wide array of observing systems such as geostationary/polar orbiting satellites, aircraft reconnaissance and radars were not available. Detection of tropical storms and hurricanes in the second half of the 19th Century was limited to those tropical storms and hurricanes that affected ships and those that impacted land. In general, the data should be slightly more complete for the years 1886 to 1910, than in the preceding decades because of some improvements in the monitoring network during this period. Improvements in the monitoring of Atlantic tropical storms and hurricanes for the 19^{th} and early 20^{th} centuries can be summarized in the following timeline (Fitzpatrick 1999, Neumann et al. 1999):

1800s: Ship logs provided tropical cyclone observations (after returning to port)

1845: First telegraph line completed from Washington, D.C. to Boston

1846: The cup anemometer invented by Robinson

1848: Smithsonian Institute volunteer weather observer network started in United States

1870: U.S. national meteorological service begun through the Army Signal Corps

1875: First hurricane forecasting system started by Benito Vines in Cuba

1890: U.S. weather service transferred to civilian agency - U.S. Weather Bureau

1898: U.S. Weather Bureau establishes observation stations throughout Caribbean

1905: Transmitted ship observations of tropical storms and hurricanes (via radio)

Note that until the invention of radio (1902), the only way to obtain ship reports of hurricanes at sea was after the ships made their way back to port. Observations from ship reports were not of use to the fledgling weather services in the United States and Cuba operationally, though some of them were available for post-season analyses of the tropical cyclone activity. These ship reports – many not collected previously - proved to be invaluable to Ludlum (1963), Ho (1989) and Partagas and Diaz (1995a, 1995b, 1996b, 1996c, 1997) and others in their historical reconstruction of past hurricanes.

While geographical positions of tropical cyclones in HURDAT were estimated to the nearest 0.1 degrees latitude and longitude (~6 nmi or ~11 km), the average errors were typically much larger in the late 19th and early 20th Centuries than this precision might imply (Table 7). Holland (1981) demonstrated that even with the presence of numerous ships and buoys in the vicinity of a strong tropical cyclone that was also monitored by aircraft reconnaissance, there were substantial errors in estimating its exact center position from the ship and buoy data alone. Based upon this, storms documented over the open ocean during the period of 1851 to 1885 were estimated to have position errors that averaged 120 nmi (220 km), with ranges of 180 to 240 nmi (330 to 440 km) errors being quite possible. In the later years of 1886 to 1910, this is improved somewhat to average position errors of around 100 nmi (185 km). At landfall, knowledge of the location of the tropical cyclone was generally more accurate, as long as the storm came ashore in a relatively populated region (Table 7). Users should consult the corresponding center fix files to see if there are actual location center fixes available from ships or coastal observations. If so, the location error for the nearest six-hourly best track position would be smaller - on the order of 30 nmi (55 km).

Storm intensity values for 1851 to 1885 were estimated to the nearest 10 kt (5 m s^{-1}), but were likely to have large uncertainty as well (Table 7). Starting in 1886, winds were given in intervals of 5 kt (2.5 m s^{-1}), consistent with the previous version of HURDAT. Best track intensity estimates for 1851 to 1910 were based mainly upon observations by ships at sea, which more often than not, would not sample the very worst part of the storm (typically only 30-60 nmi (55-110 km) in diameter). Holland (1981) demonstrated that even in a relatively data-rich region of ship and buoy observations within the circulation of a tropical cyclone, the actual intensity was likely to be substantially underestimated. Figures 3 and 4 provide a graphic demonstration of this for Major Hurricane Erin of 2001 that made a close by-pass of Bermuda. Aircraft winds extrapolated to the ocean surface indicated maximum sustained surface winds of just above 100 kt (51 m s^{-1}) in Major Hurricane Erin (Figure 3). However, despite transiting within 85 nmi (160 km) of Bermuda, the highest observed surface winds from ships and coastal stations were only around 40 kt (20 m s^{-1}) (Figure 4). Such an underestimation of tropical cyclone intensities was likely common in the pre-satellite and pre-aircraft reconnaissance era. It was estimated that the intensity measurements for 1851 to 1885 were in error an average of 25 kt (13 m s^{-1}) over the open ocean, with a bias toward underestimating the true intensity (Table 7). For the later period of 1886 to 1910, this was slightly improved – to an average error of 20 kt (10 m s^{-1}) over the ocean. At landfall, intensity estimates were improved and show a negligible bias as long as the landfall occurs over a populated coastline (Table 7).

3f.) Metadata Files

All Atlantic basin tropical storms and hurricanes in the new best track database are accompanied by a "metadata file". This file consists of a descriptive paragraph about the particular storm of interest that provides information about the sources that went into creating the best track, whether or not a wind-pressure relationship was utilized, if the Kaplan and DeMaria (1995, 2001) wind decay models were used for inland wind estimates, and any other pertinent information. Storms and hurricanes for which the entire lifecycle is available during the period of 1851 to 1885 (from genesis as a tropical storm, to peak intensity, to decay to minimal tropical storm or transformation to an extratropical storm) are so indicated in the metadata file. If this is not indicated in the metadata file, users of the data are cautioned that only a partial lifecycle of the particular storm is available. Since documenting the full lifecycle of tropical cyclones became somewhat more frequent starting in 1886, only those tropical cyclones that lack archival of their full lifecycle are so noted in the metadata files for the years 1886 to 1910. All of the tropical storms and hurricanes for the period of 1851-1910 are considered “UNNAMED”. However, many of these storms have been recognized by various informal names. These are included in the metadata file when at all possible. Below is the metadata file for Storm 1, 1856:

> 1856/01: Utilized Ho's (1989) work - apparently not used in Partagas and Diaz's (1995a) analysis - to alter the track and intensity near the US. Inland winds over SE US reduced via Kaplan and DeMaria's (1995) inland decay model. Ship with pressure measurement of 955 mb not in the hurricane's eye suggests at least 105 kt with the Gulf of Mexico wind-pressure relationship, utilize 130 kt in best track. Ho's estimate of 934 mb at landfall gives 125 kt, utilize 130 kt in best track - a major hurricane. A small RMW of 12 nmi supports slight increase of winds over suggested wind-pressure relationship. Surge value of 11-12' provided by Ludlum (1963) for Last Island, Louisiana. The storm is also known as the “Last Island Hurricane” after the destruction caused at that location.

For the cases where Partagas and Diaz or the original HURDAT had listed a storm, but it was not for some reason included into the revised HURDAT, an addendum to the Metadata File for that year is included. For example, here is a case for 1851:

> 1851 - Additional Notes:
> 1. The tropical storm listed as #5 in 1851 in Partagas and Diaz (1995a) was not included into the HURDAT because of the lack of evidence to suggest that the storm actually existed. Partagas and Diaz had found an unsupported reference to it in Tannehill (1938), but no other information.

3g.) United States Tropical Cyclones

Tables 8 and 9 summarize the continental U.S. hurricanes and tropical storms, respectively, for the years 1851-1910 and the states impacted by these systems. U. S. hurricanes are defined as those hurricanes that are analyzed to cause maximum sustained (1 min) surface (10 m) winds of at least 64 kt (33 m/s) for an open exposure on the coast or inland in the continental United States. Both hurricanes that make a direct landfall as well as those that make a close bypass are considered. Likewise, U.S. tropical storms are those that produced winds of 34 to 63 kt (18 to 32 m/s) at the coast or inland. In addition to the parameters also common to HURDAT (e.g. latitude, longitude, maximum sustained winds and central pressure), the U.S. hurricane compilation also includes - where available - the RMW, peak observed storm surge and environmental pressure. For the period of 1851 to 1899, the timing of U.S. landfalls is estimated to the nearest hour; while for the later years of 1900 to 1910, the more complete observational network allowed for an indication of U.S. hurricanes and tropical storms to the nearest 10 minutes of landfall. As was utilized in HURDAT, maximum sustained wind speeds are estimated to the nearest 10 kt for the years of 1851 to 1885, while a more precise measure of 5 kt increments are used for the period of 1886 to 1910.

As mentioned earlier, because of the lack of continuously populated coastal regions over this era, this record represents an incomplete listing of the frequency and intensity of tropical cyclones that have impacted the United States. Based upon analysis of "settled regions" (defined as at least two inhabitants per square mile) from U.S. Census reports and other historical analyses (Department of the Interior 1895, Kagan 1966, and Tanner 1995), estimated dates are provided for when accurate tropical cyclone records began in specified regions of the United States (Table 10). Prior to these dates, tropical storms or hurricanes -especially smaller systems like Andrew in 1992 and Bret in 1999 - might have been missed completely or may have had their true intensity underestimated.

As an example of the intensity underestimation bias of a landfalling hurricane along a relatively uninhabited coastal region, consider the case of Storm 2, 1882. This tropical cyclone had been characterized by Dunn and Miller (1960) as a “minimal” storm in northwest Florida based upon a minimum sea level pressure measurement of just 994 mb and a 50 kt (26 m s^{-1}) wind observed at Pensacola. However, only hours before landfall the barkentine "Cato" measured a central pressure of 949 mb, an observation apparently unknown to Dunn and Miller. Thus, this storm was likely a major hurricane at landfall, though the intense inner core missed making a direct strike on any populated areas. It is certain that many other storms (both in the U.S. and other land masses) made landfall without ships or coastal communities sampling the intense inner core, resulting in an underestimation of their intensity at landfall. Such underestimations of landfall intensity are particularly problematic for locations such as south Florida, where, for example, Miami was not incorporated until 1896. There is less uncertainty for an area like New England, which has been fairly densely populated since well before the 1850s. Despite these limitations, this analysis does allow for extending the accurate historical record back in time for several locations along the U.S. coastline.

For some U.S. hurricanes, a central pressure estimate was obtained from the work of Ho et al. (1987), Ho (1989) or other references (so noted in the metadata file for the appropriate storms), which was then used to estimate maximum wind speeds through application of one of the new wind-pressure relationships. If no measured or analyzed (via the Ho [1989] methodology) central pressure was described in the metadata file, then the winds at landfall were determined from coastal station observations or ships immediately offshore, destruction at the coast and/or observed storm surge values. In general, it was extremely rare for land-based anemometers to actually measure what was suspected to be the maximum sustained surface winds. This was due to the relative sparsity of coastal stations combined with the small RMW typical of hurricanes as well as the inability of anemometers of the era to survive in extreme wind events. In the cases where there was no central pressure value directly available, the estimated winds at landfall were then used via the wind-pressure relationship to back out a reasonable central pressure. In either case, the objective was to provide both an estimate of the maximum sustained wind at landfall and a central pressure for all U.S. hurricanes.

3h.) Evaluation of the HURDAT Revision by NHC

This re-analysis effort has been done with considerable interaction with the hurricane specialists and researchers at the National Hurricane Center. The HURDAT database has been maintained and updated yearly by NHC for decades. Thus all revisions to the existing best track (or extensions back in time as is the case for the period of 1851 to 1885) have been examined and approved by the NHC Best Track Change Committee. Comments by the NHC Best Track Change Committee and the authors' replies back to the Committee are also available via the HURDAT re-analysis web page.

4.) Future Re-analysis Work

Historical tropical cyclone reconstructions are inevitably subject to revisions whenever new archived information is uncovered. Thus while several thousand alterations and additions to HURDAT have been completed for the years 1851 to 1910, this does not insure that there may not be further changes once new information is made available. Such an archive of historical data – especially one based upon quasi-objective interpretations of limited observations – should always be one that can be revised when more data or better interpretations of exisiting information becomes available.

However, much more work still needs to be accomplished for the Atlantic hurricane database. One essential project is a Partagas and Diaz style re-analysis for both the years before

1851 and for the pre-aircraft reconnaissance era of 1911 to 1943. The former may lead to a complete dataset of U.S. landfalling hurricanes for the Atlantic coast from Georgia to New England back to at least 1800, given the relatively high density of population extending that far into the past. The latter project would likely yield a much higher quality dataset for the entire Atlantic basin – especially for frequency and intensity of tropical cyclones – given the availability of revised compilations of ship data (e.g. Comprehensive Ocean-Atmosphere Data Set, Woodruff et al. 1987). Another possibility is to re-examine the intensity record of tropical cyclones since 1944 by utilizing the original aircraft reconnaissance data in the context of today's understanding of tropical cyclone eyewall structure and best extrapolations from flight-level winds to the surface winds (e.g. Dunion et al. 2002). Finally, efforts could be directed to extending the scope of the HURDAT database to include other parameters of interest, such as RMW and radii of gale and hurricane force winds by quadrant.

Regardless of the final direction pursued by future research into the re-analysis of Atlantic hurricanes, it is hoped that efforts detailed here have already expanded the possibilities for the utilization of the Atlantic hurricane database. Users now have access to a more complete record of Atlantic hurricanes, one that extends further back in time and one that provides more information regarding the limitations and error sources. In any planning for the future, a thorough appreciation of past events helps one prepare for possibilities to come. Atlantic hurricanes, arguably the most destructive of all natural phenomena in the Western Hemisphere, demand our attention for their understanding to better prepare society for the impacts that they bring. This re-analysis of Atlantic basin tropical storms and hurricanes that now provide users with 150 years of record may be able to assist in such endeavors in at least a small way.

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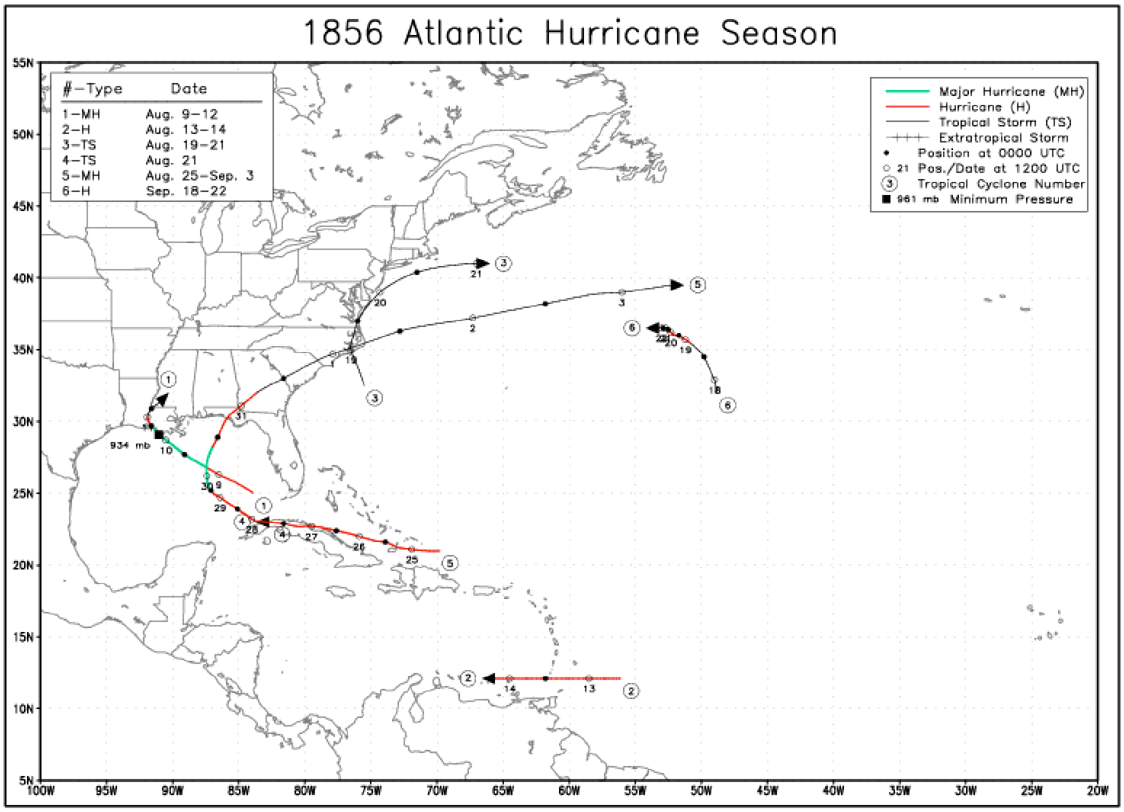

Figure 1: Reconstructed Atlantic tropical cyclone tracks and intensities for 1856.

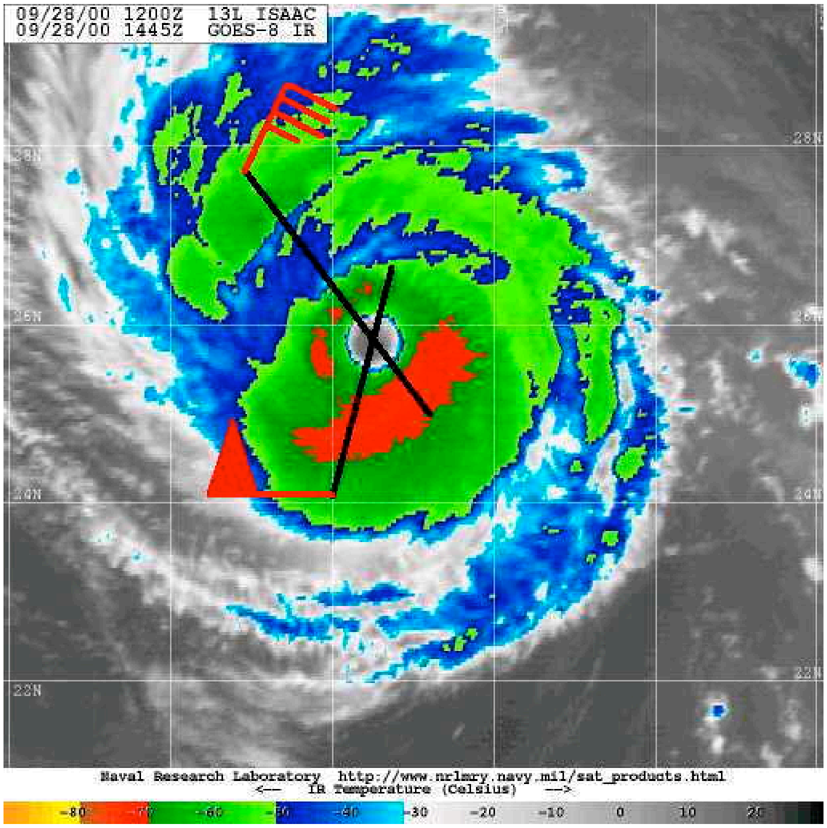

Figure 2: An idealized representation for finding the center of a tropical cyclone based upon peripheral wind observations. Two ship observations (indicated by the red wind barbs) roughly indicate the tropical cyclone center (where the two black lines cross) assuming cyclonic flow with a 20º inflow angle.

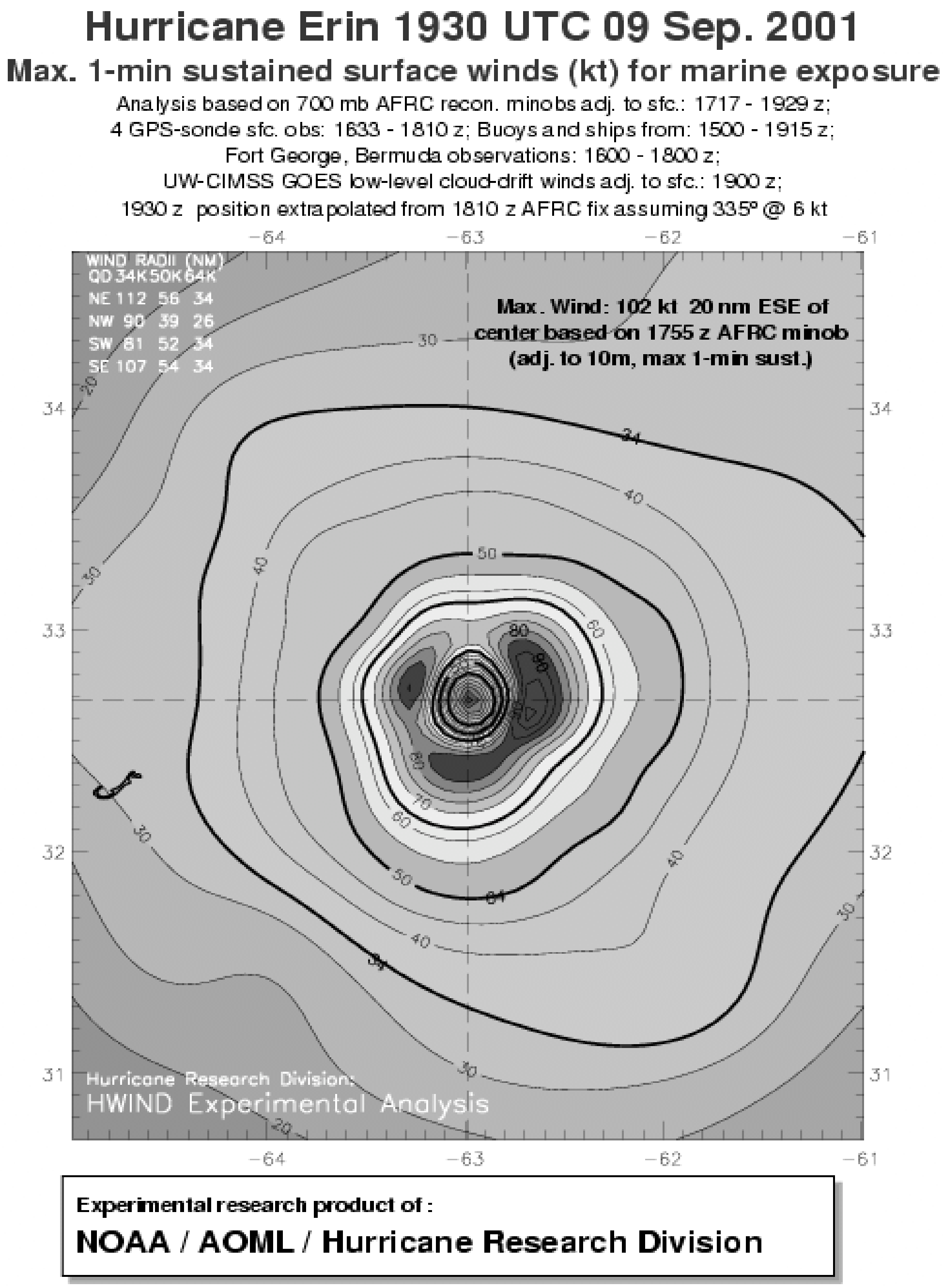

Figure 3: Surface windfield analysis for Major Hurricane Erin on 9 September 2001 at 1930 UTC. This analysis utilizes all available surface and near surface wind data including surface-reduced aircraft reconnaissance winds, surface-reduced cloud-drift winds, and ship and buoy observations. These data are all storm-relative composited for the period of 1500 to 1900 UTC, 9 September 2001 and are adjusted to a standard maximum sustained surface (1 min, 10 m) measurement. Peak sustained winds are analyzed to be 102 kt (52 m s^{-1}) to the east-southeast of Erin's center at a radius of 20 nmi (37 km).

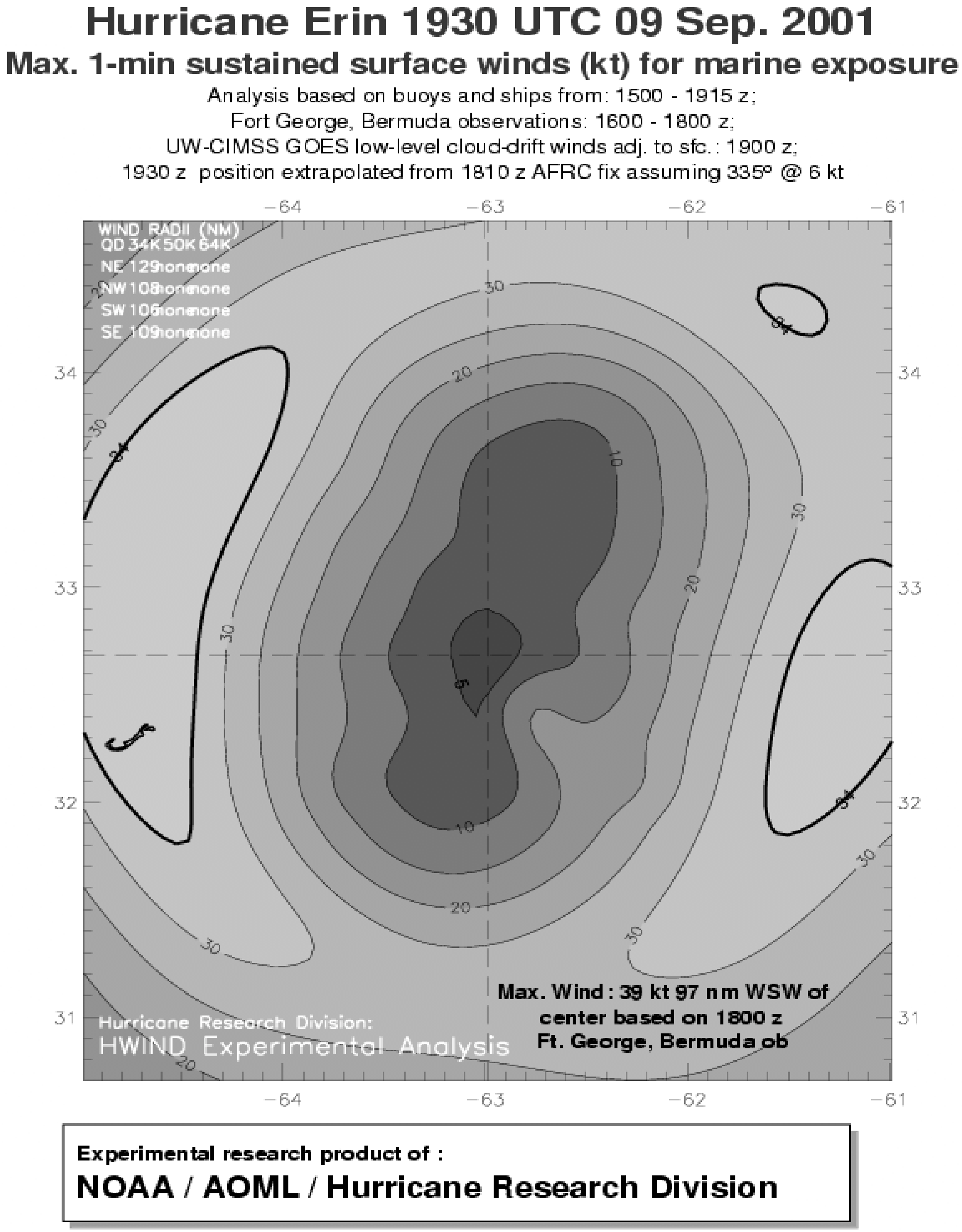

Figure 4: Same as Figure 3, but without the benefit of surface-reduced aircraft reconnaissance flight-level winds. In this case, highest analyzed surface winds were only 39 kt (20 m s^{-1}) based upon observations from Bermuda about 100 nmi (160 km) from Erin's center. Such an analysis is typical of data available before the advent of aircraft reconnaissance data in the mid-1940s and is illustrative of the underestimation bias that occurred for many tropical cyclones during the era of the late 19^{th} and early 20^{th} Centuries being re-analyzed.

Table 1: <u>Sources utilized by Partagas and Diaz in their original work:</u>
Ship reports published in *The New York Times*, *The Times* (London) and *Gaceta de la Habana*, the *Monthly Weather Review* individual storm and seasonal summaries, the Historical Weather Maps series, reports of the Chief of the Weather Bureau (U.S.), Academia de Ciencias (1970), Alexander (1902), Cline (1926), Dunn and Miller (1960), Garcia-Bonnelly (1958), Garriott (1900), Gutierrez-Lanza (1904), Ho et al. (1987), Instituto Cubano de Geodesia y Cartografia (1978), Ludlum (1963), Martinez-Fortun (1942), Mitchell (1924), Neumann et al. (1993), Ortiz-Hector (1975), Rappaport and Partagas (1995), Rodriguez-Demorizi (1958), Rodriguez-Ferrer (1876), Salivia (1972), Sarasola (1928), Simpson and Riehl (1981), Sullivan (1986), Tannehill (1938), Tucker (1982), Vines (1877), and Vines (1895).

<u>Sources utilized in the re-analysis effort beyond those listed above:</u>
Abraham et al. (1998), Barnes (1998a, 1998b), Boose et al. (2001, 2002), Coch and Jarvinen (2000), Connor (1956), Doehring et al. (1994), Ellis (1988), Hebert and McAdie (1997), Ho (1989), Hudgins (2000), Jarvinen (1990), Jarrell et al. (1992), Neumann et al. (1999), Parkes et al. (1998), Perez et al. (2000), Roth (1997a, 1997b), Roth and Cobb (2000, 2001), Sandrik (2002), and Sandrik and Jarvinen (1999).

Table 2a: "Center fix" intensity measurement data for Storm 1, 1856.

1856/01 (Synoptic/intensity):

Date	Time	Wind/Dir.	Pressure[1]	Location		Source[2]
8/10/1856	???? UTC	40 kt/??	???? mb	29.3N	89.9W	Fort Livingston
8/10/1856	???? UTC	60 kt/??	???? mb	30.3N	91.4W	Iberville Parish
8/10/1856	0900 UTC	70 kt/N-S	955 mb	28.6N	90.2W	"C.D. Mervin"
8/10/1856	1400 UTC	40 kt/E	???? mb	30.0N	90.1W	New Orleans
8/10/1856	2100 UTC	70 kt/??	???? mb	29.0N	90.9W	Last Island
8/10/1856	2200 UTC	70 kt/??	???? mb	29.7N	91.2W	Bayou Boeuf
8/11/1856	???? UTC	40 kt/??	???? mb	30.4N	91.2W	Baton Rouge
8/11/1856	???? UTC	40 kt/??	???? mb	32.2N	91.1W	New Carthage
8/11/1856	???? UTC	60 kt/??	???? mb	31.6N	91.4W	Natchez

1) If the sea level pressure measurement was determined to be a "central pressure", a "C" was indicated after the value. Otherwise, the pressure value was considered to be a peripheral (either eyewall or rainband environment of the storm) observation.

2) Sources are either from coastal or inland station data or from ship data (in quotation marks).

Table 2b. "Center fix" intensity position data for Storm 5, 1852.

1852/05 (Center positions):

Date	Time	Location		Source[1]
10/09/1852	???? UTC	25.6N	86.5W	"Hebe"

1) Sources are either from coastal or inland station data or from ship data (in quotation marks).

Table 3: The Beaufort Wind Scale (Fitzpatrick 1999).

Beaufort Number	Knots	Description	Specifications at Sea
0	< 1	Calm	Sea like a mirror
1	1-3	Light air	Ripples with the appearance of scales are formed, but without foam crest
2	4-6	Light breeze	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break
3	7-10	Gentle breeze	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses
4	11-16	Moderate breeze	Small waves, becoming longer; fairly frequent white horses
5	17-21	Fresh breeze	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray)
6	22-27	Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray)
7	28-33	Near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks in the direction of the wind
8	34-40	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks along the direction of the wind
9	41-47	Strong gale	High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple, tumble, and roll over; spray may affect visibility
10	48-55	Storm	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes on a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility affected
11	56-63	Violent storm	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of wave crests are blown into froth; visibility affected
12	> 63	Hurricane	The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected

Table 4: The Smithsonian Institute and Military Fort Wind Force Scale (Ludlum 1963, Ho 1989, M. Chenoweth, personal communication, 2001). Values are estimates of the highest gusts.

1 - Very light breeze	2 mph (2 kt)
2 - Gentle breeze	4 mph (4 kt)
3 - Fresh breeze	12 mph (10 kt)
4 - Strong breeze	25 mph (22 kt)
5 - High breeze	35 mph (30 kt)
6 - Gale	45 mph (39 kt)
7 - Strong gale	60 mph (51 kt)
8 - Violent gale	75 mph (65 kt)
9 - Hurricane	90 mph (78 kt)
10 - Most violent	100 mph (87 kt)

Table 5: Newly developed regionally-based wind-pressure relationships for the Atlantic basin. Winds are maximum sustained surface winds in knots and pressures are central pressures in mb at sea level.

P(MB)	GMEX	<25N	25-35N	35-45N	KRAFT	DVORAK
1000	45	47	48	49	50	45
990	62	64	63	63	67	61
980	76	78	75	73	80	76
970	89	89	85	82	92	90
960	100	100	94	90	102	102
950	110	110	103	97	111	113
940	119	119	110	103	120	122
930	128	127	117	---	128	132
920	137	135	124	---	135	141
910	145	143	---	---	142	151
900	153	150	---	---	149	161
890	---	157	---	---	---	170

Table 6: Best track information for Storm 1, 1856 in the standard HURDAT format (a) and in an "easy-to-read" version (b).

(a)

```
00820 08/09/1856 M= 4  1 SNBR=  29 NOT NAMED   XING=1 SSS=4
00825 08/09*250 839  70    0*257 851  80    0*263 865  90    0*270 878 100    0
00830 08/10*277 891 110    0*282 898 120    0*287 905 130    0*292 911 130  934
00835 08/11*297 916 110    0*300 918  80    0*303 919  60    0*306 918  50    0
00840 08/12*309 916  40    0*313 910  40    0*  0   0   0    0*  0   0   0    0
00845 HR LA4
```

(b)

```
Month Day Hour   Lat.   Long.   Dir.     ______Speed_____   _____Wind________ Pressure   Type
  8    9   0 UTC  25.0N  83.9W      deg     mph/     km/hr   80 mph/130 km/hr      mb  H-Cat. 1
  8    9   6 UTC  25.7N  85.1W  305 deg  13 mph/ 22 km/hr   90 mph/150 km/hr      mb  H-Cat. 1
  8    9  12 UTC  26.3N  86.5W  295 deg  14 mph/ 24 km/hr  100 mph/170 km/hr      mb  H-Cat. 2
  8    9  18 UTC  27.0N  87.8W  300 deg  14 mph/ 24 km/hr  120 mph/190 km/hr      mb  MH-Cat. 3
  8   10   0 UTC  27.7N  89.1W  300 deg  14 mph/ 24 km/hr  130 mph/200 km/hr      mb  MH-Cat. 3
  8   10   6 UTC  28.2N  89.8W  310 deg   8 mph/ 12 km/hr  140 mph/220 km/hr      mb  MH-Cat. 4
  8   10  12 UTC  28.7N  90.5W  310 deg   8 mph/ 12 km/hr  150 mph/240 km/hr      mb  MH-Cat. 4
  8   10  18 UTC  29.2N  91.1W  315 deg   8 mph/ 12 km/hr  150 mph/240 km/hr  934 mb  MH-Cat. 4 - Landfall
  8   11   0 UTC  29.7N  91.6W  320 deg   6 mph/ 11 km/hr  130 mph/200 km/hr      mb  MH-Cat. 3
  8   11   6 UTC  30.0N  91.8W  330 deg   3 mph/  5 km/hr   90 mph/150 km/hr      mb  H-Cat. 1
  8   11  12 UTC  30.3N  91.9W  345 deg   3 mph/  5 km/hr   70 mph/110 km/hr      mb  TS
  8   11  18 UTC  30.6N  91.8W   15 deg   3 mph/  5 km/hr   60 mph/ 90 km/hr      mb  TS
  8   12   0 UTC  30.9N  91.6W   30 deg   3 mph/  5 km/hr   50 mph/ 70 km/hr      mb  TS
  8   12   6 UTC  31.3N  91.0W   50 deg   6 mph/ 11 km/hr   50 mph/ 70 km/hr      mb  TS
```

Table 7: Estimated average position and intensity errors in best track for the years 1851-1910. Negative bias errors indicate an underestimation of the true intensity.

Situation	Dates	Position Error	Intensity Error (absolute)	Intensity Error (bias)
Open ocean	1851-1885	120 nmi/220 km	25 kt/13 m s^{-1}	-15 kt/-8 m s^{-1}
	1886-1910	100 nmi/185 km	20 kt/10 m s^{-1}	-10 kt/-5 m s^{-1}
Landfall at sparsely populated area	1851-1885	120 nmi/220 km	25 kt/13 m s^{-1}	-15 kt/-8 m s^{-1}
	1886-1910	100 nmi/185 km	20 kt/10 m s^{-1}	-10 kt/-5 m s^{-1}
Landfall at settled area	1851-1885	60 nmi/110 km	15 kt/8 m s^{-1}	0 kt/0 m s^{-1}
	1886-1910	60 nmi/110 km	12 kt/6 m s^{-1}	0 kt/0 m s^{-1}

Table 8: Continental United States Hurricanes: 1851-1910

#/Date	Time	Lat	Lon	Max Winds	Saffir-Simpson	RMW	Storm Surge	Central Pressure	Environ. Pressure	States Affected
1-6/25/1851$	1200Z	28.5N	96.5W	70kt	1	---	---	(985mb)	------	BTX1
4-8/23/1851$	2100Z	30.1N	85.7W	100kt	3	---	12'%	(960mb)	------	AFL3,GA1
1-8/22/1852$*	1200Z	23.8N	81.3W	80kt	1	---	---	(977mb)	------	BFL1
1-8/26/1852	0600Z	30.2N	88.6W	100kt	3	30nmi	12'%	961mb	------	AL3,MS3,LA2,AFL1
3-9/12/1852$	0000Z	28.0N	82.8W	70kt	1	---	---	(985mb)	------	BFL1
5-10/9/1852$	2100Z	29.9N	84.4W	90kt	2	---	7'%	(969mb)	------	AFL2,GA1
8-10/21/1853*	0600Z	30.9N	80.9W	70kt	1	---	---	(965mb)	------	GA1
2-9/8/1854	2000Z	31.7N	81.1W	100kt	3	40nmi	---	950mb	------	GA3,SC2,DFL1
3-9/18/1854	2100Z	28.9N	95.3W	90kt	2	---	---	(969mb)	------	BTX2
6-9/16/1855$	0300Z	29.2N	89.5W	110kt	3	---	10-15'%	(950mb)	------	LA3,MS3
1-8/10/1856$	1800Z	29.2N	91.1W	130kt	4	12nmi	11-12'%	934mb	------	LA4
5-8/31/1856$	0600Z	30.2N	85.9W	90kt	2	---	6'%	(969mb)	------	AFL2,AL1,GA1
2-9/13/1857&	1100Z	35.2N	75.7W	80kt	1	---	---	961mb	------	NC1
3-9/16/1858	1700Z	40.9N	72.2W	80kt	1	45nmi	---	(976mb)	------	NY1
3-9/16/1858	1800Z	41.3N	72.0W	70kt	1	45nmi	---	979mb	------	CT1,RI1,MA1
5-9/16/1859	0000Z	30.3N	88.1W	70kt	1	---	---	(985mb)	------	AL1
1-8/11/1860$	2000Z	29.2N	90.0W	110kt	3	---	12'%	(950mb)	------	LA3,MS3,AL2
4-9/15/1860$	0400Z	29.3N	89.6W	90kt	2	---	10'%	(969mb)	------	LA2,MS2,AL1
6-10/2/1860$	1700Z	29.5N	91.4W	90kt	2	---	---	(969mb)	------	LA2
2-8/16/1861$*	0000Z	24.2N	82.0W	70kt	1	---	---	(970mb)	------	BFL1
5-9/27/1861	1700Z	34.5N	77.4W	70kt	1	---	---	(985mb)	------	NC1
8-11/2/1861	1000Z	34.7N	76.6W	70kt	1	---	---	(985mb)	------	NC1
4-9/13/1865$	2100Z	29.8N	93.4W	90kt	2	---	---	(969mb)	------	LA2,CTX1
7-10/23/1865$	1000Z	24.6N	81.7W	90kt	2	---	---	(969mb)	------	BFL2
7-10/23/1865$	1400Z	25.4N	81.1W	90kt	2	---	---	(969mb)	------	BFL2,CFL1
1-7/15/1866	1200Z	28.5N	96.5W	90kt	2	---	---	(969mb)	------	BTX2
1-6/22/1867	1400Z	32.9N	79.7W	70kt	1	---	---	(985mb)	------	SC1
7-10/2/1867$#	1500Z	25.4N	97.1W	70kt	1	---	---	(969mb)	------	ATX1
7-10/4/1867$	1500Z	29.2N	91.0W	90kt	2	---	7'%	(969mb)	------	LA2,CTX1
7-10/6/1867$	1500Z	29.6N	83.4W	70kt	1	---	---	(985mb)	------	AFL1
2-8/17/1869	0700Z	28.1N	96.8W	90kt	2	---	---	(969mb)	------	BTX2
5-9/5/1869$	1200Z	29.2N	90.0W	70kt	1	---	---	(985mb)	------	LA1
6-9/8/1869&	2100Z	41.0N	71.9W	80kt	1	30nmi	---	963mb	------	NY1
6-9/8/1869	2200Z	41.4N	71.7W	100kt	3	30nmi	8'%	965mb	------	RI3,MA3,CT1
10-10/4/1869&	1900Z	41.3N	70.5W	80kt	1	30nmi	---	(965mb)	------	MA1
10-10/4/1869&	2000Z	41.7N	70.4W	80kt	1	30nmi	---	(965mb)	------	MA1
10-10/4/1869	2300Z	43.7N	70.1W	90kt	2	---	---	(968mb)	------	ME2
1-7/30/1870	1800Z	30.5N	88.0W	70kt	1	---	---	(985mb)	------	AL1
6-10/10/1870$*	0500Z	24.6N	80.8W	70kt	1	---	---	(970mb)	------	BFL1,CFL1
9-10/20/1870$	1400Z	24.7N	82.8W	80kt	1	---	---	(977mb)	------	BFL1
9-10/20/1870$	2000Z	26.0N	81.6W	80kt	1	---	---	(977mb)	------	BFL1
3-8/17/1871$	0200Z	27.1N	80.2W	100kt	3	30nmi	---	955mb	1016mb	CFL3,DFL1,AFL1
4-8/25/1871$	0500Z	27.6N	80.3W	90kt	2	---	---	(965mb)	------	CFL2,DFL1
6-9/6/1871$	1400Z	29.2N	83.0W	70kt	1	---	---	(985mb)	------	AFL1
3-9/19/1873$	1500Z	29.9N	84.4W	70kt	1	---	---	(985mb)	------	AFL1
5-10/7/1873$	0100Z	26.5N	82.2W	100kt	3	26nmi	14'%	959mb	1014mb	BFL3,CFL2,DFL1
6-9/28/1874$	0300Z	29.1N	82.9W	70kt	1	---	---	(985mb)	------	AFL1
6-9/28/1874	1800Z	32.8N	80.0W	80kt	1	---	---	981mb	------	SC1,NC1
3-9/16/1875	2100Z	27.7N	97.2W	100kt	3	---	15'%	(960mb)	------	BTX3,ATX2
2-9/17/1876	1400Z	34.4N	77.6W	80kt	1	---	---	980mb	------	NC1,VA1
5-10/20/1876$	0500Z	25.8N	81.4W	90kt	2	---	---	973mb	------	BFL2,CFL1
2-9/18/1877$	1600Z	29.2N	91.0W	70kt	1	---	---	(985mb)	------	LA1
2-9/19/1877$	2000Z	30.4N	86.6W	70kt	1	---	---	(985mb)	------	AFL1
4-10/3/1877$	0500Z	30.0N	85.5W	100kt	3	---	12'%	(960mb)	------	AFL3,GA1
5-9/10/1878$	1100Z	28.6N	82.6W	90kt	2	---	---	(970mb)	1010mb	BFL2,DFL1
5-9/12/1878	1200Z	32.5N	80.4W	80kt	1	---	---	(976mb)	------	NC1,SC1,GA1
11-10/23/1878	0400Z	34.8N	77.1W	90kt	2	---	12’%	(963mb)	------	NC2,VA1,MD1,DE1,NJ1,PA1
2-8/18/1879	1200Z	34.7N	76.7W	100kt	3	16nmi	7’	971mb	1014mb	NC3,VA2
2-8/19/1879&	0600Z	41.4N	70.8W	60kt	TS	---	---	984mb	------	(None)
3-8/23/1879	0200Z	29.4N	94.4W	90kt	2	---	---	964mb	------	CTX2,LA2
4-9/1/1879$	1600Z	29.5N	91.4W	110kt	3	---	---	(950mb)	------	LA3
2-8/13/1880#	0100Z	25.8N	97.0W	110kt	3	12nmi	---	931mb	------	ATX3
4-8/29/1880$	1200Z	28.2N	80.6W	90kt	2	---	---	972mb	------	CFL2,DFL1
4-8/31/1880	0400Z	29.7N	84.8W	70kt	1	---	---	(985mb)	------	AFL1
6-9/9/1880	1000Z	34.7N	77.1W	70kt	1	---	---	987mb	------	NC1
9-10/8/1880	1900Z	28.9N	82.7W	70kt	1	---	---	(985mb)	------	AFL1

5-8/28/1881	0200Z	31.7N	81.1W	90kt	2	15nmi	---	970mb	------	GA2,SC1
6-9/9/1881	1600Z	33.9N	78.1W	90kt	2	15nmi	---	975mb	------	NC2
2-9/10/1882	0200Z	30.4N	86.8W	100kt	3	---	---	949mb	------	AFL3,AL1
3-9/15/1882	0500Z	29.8N	93.7W	90kt	2	---	---	(969mb)	------	LA2,CTX1
6-10/11/1882	0400Z	29.5N	83.3W	70kt	1	---	---	(985mb)	------	AFL1
3-9/11/1883	1300Z	33.9N	78.5W	90kt	2	---	---	(965mb)	------	NC2,SC1
2-8/25/1885	0900Z	32.2N	80.7W	100kt	3	---	---	(953mb)	------	SC3,NC2,GA1,DFL1
1-6/14/1886	1600Z	29.6N	94.2W	85kt	2	---	7'%	(973mb)	------	CTX2,LA2
2-6/21/1886	1100Z	30.1N	84.0W	85kt	2	---	---	(973mb)	------	AFL2,GA1
3-6/30/1886	2100Z	29.7N	85.2W	85kt	2	---	---	(973mb)	------	AFL2
4-7/19/1886	0100Z	28.8N	82.7W	70kt	1	---	---	(985mb)	------	AFL1
5-8/20/1886	1300Z	28.1N	96.8W	135kt	4	15nmi	15'	925mb	------	BTX4
8-9/23/1886#	0700Z	26.0N	97.2W	80kt	1	---	---	(973mb)	------	ATX1,BTX1
10-10/12/1886	2200Z	29.8N	93.5W	105kt	3	---	12'%	(955mb)	------	LA3,CTX2
4-7/27/1887	1500Z	30.4N	86.6W	75kt	1	---	---	(981mb)	------	AFL1
6-8/20/1887*	1200Z	35.0N	75.0W	65kt	1	---	---	(946mb)	------	NC1
9-9/21/1887	1700Z	26.1N	97.2W	85kt	2	---	---	973mb	------	ATX2
13-10/19/1887	0200Z	29.1N	90.4W	75kt	1	---	---	(981mb)	------	LA1
1-6/17/1888	0600Z	28.7N	95.7W	70kt	1	---	---	(985mb)	------	BTX1
3-8/16/1888$	1900Z	25.8N	80.1W	100kt	3	---	14'%	(953mb)	------	CFL3,BFL1
3-8/19/1888	1600Z	29.1N	90.7W	95kt	2	---	---	(964mb)	------	LA2
6-9/26/1888&	1300Z	41.6N	69.9W	55kt	TS	---	---	985mb	------	(None)
7-10/11/1888	0100Z	29.2N	83.1W	95kt	2	11nmi	9'	970mb	------	AFL2,DFL1
6-9/23/1889	0400Z	29.1N	89.8W	70kt	1	---	---	(985mb)	------	LA1
1-7/5/1891	2200Z	28.8N	95.5W	80kt	1	---	---	(977mb)	------	BTX1,CTX1
3-8/24/1891$	1500Z	25.4N	80.2W	70kt	1	---	---	(985mb)	------	CFL1
7-10/12/1891*	1200Z	34.5N	74.0W	65kt	1	---	---	(965mb)	------	NC1
4-8/24/1893	1200Z	40.6N	73.9W	75kt	1	30nmi	---	986mb	------	NY1,VA1
6-8/28/1893	0500Z	31.7N	81.1W	100kt	3	23nmi	9-10'	954mb	1010mb	GA3,SC3,NC1,DFL1
8-9/7/1893	1400Z	29.2N	91.1W	85kt	2	---	---	973mb	------	LA2
10-10/2/1893	0800Z	29.3N	89.8W	115kt	4	12nmi	---	948mb	------	LA4
10-10/2/1893	1600Z	30.3N	88.9W	95kt	2	17nmi	10-12'%	970mb	------	MS2,AL2
9-10/13/1893	1300Z	33.0N	79.5W	105kt	3	15nmi	14'%	955mb	------	SC3,NC2,VA1
4-9/25/1894$	1100Z	24.7N	82.0W	80kt	1	---	---	985mb	------	BFL1
4-9/25/1894$	1900Z	26.5N	82.0W	90kt	2	---	---	(975mb)	------	BFL2,DFL1
4-9/27/1894	0700Z	32.3N	80.7W	80kt	1	---	10'%	(976mb)	------	SC1
4-9/29/1894*	1200Z	37.0N	75.0W	70kt	1	---	---	(978mb)	------	VA1
5-10/9/1894	0300Z	30.2N	85.5W	105kt	3	---	---	(955mb)	------	AFL3,GA1
5-10/10/1894	1500Z	40.7N	72.9W	75kt	1	---	---	(978mb)	------	NY1,RI1
2-8/30/1895#	0400Z	25.0N	97.6W	65kt	2	---	---	(973mb)	------	ATX1
1-7/7/1896	1700Z	30.4N	86.5W	85kt	2	---	---	(973mb)	------	AFL2
2-9/10/1896	1300Z	41.2N	70.6W	70kt	1	30nmi	---	(985mb)	------	RI1,MA1
4-9/29/1896	1100Z	29.2N	83.1W	110kt	3	15nmi	---	960mb	1014mb	AFL3,DFL3,GA2,SC1,NC1,VA1
2-9/13/1897	0500Z	29.7N	93.8W	75kt	1	---	6'%	(981mb)	------	LA1,CTX1
1-8/2/1898	2300Z	29.7N	84.8W	70kt	1	---	---	(985mb)	------	AFL1
2-8/31/1898	0700Z	32.1N	80.8W	75kt	1	---	---	(980mb)	------	GA1,SC1
7-10/2/1898	1600Z	30.9N	81.4W	115kt	4	18nmi	16'	938mb	1010mb	GA4,DFL2
2-8/1/1899	1700Z	29.7N	84.7W	85kt	2	---	---	979mb	1017mb	AFL2
3-8/18/1899	0100Z	35.2N	75.8W	105kt	3	---	---	(945mb)	1012mb	NC3
8-10/31/1899	0900Z	33.6N	79.0W	95kt	2	35nmi	9'%	955mb	1012mb	NC2,SC2
1-9/9/1900	0140Z	29.1N	95.1W	125kt	4	14nmi	20'%	931mb	1012mb	CTX4
3-7/11/1901	0720Z	36.0N	75.8W	70kt	1	---	---	(983mb)	1016mb	NC1
4-8/14/1901	2110Z	29.3N	89.6W	80kt	1	---	8'%	(973mb)	1013mb	LA1
4-8/15/1901	1700Z	30.4N	88.8W	80kt	1	33nmi	8'%	973mb	1013mb	MS1,AL1
3-9/11/1903	2250Z	26.1N	80.1W	75kt	1	43nmi	8'%	976mb	1016mb	CFL1
3-9/13/1903	2330Z	30.1N	85.6W	80kt	1	---	10'%	(977mb)	1016mb	AFL1
4-9/16/1903	1120Z	39.1N	74.7W	70kt	1	---	---	990mb	1020mb	NJ1,DE1
2-9/14/1904	1320Z	33.1N	79.2W	70kt	1	---	---	(985mb)	1017mb	SC1
3-10/17/1904	0750Z	25.3N	80.3W	70kt	1	---	---	(985mb)	1016mb	CFL1
2-6/17/1906	0240Z	24.7N	81.1W	70kt	1	---	---	(986mb)	1013mb	BFL1,CFL1
2-6/17/1906	0750Z	25.2N	80.7W	75kt	1	26nmi	---	979mb	1013mb	CFL1
5-9/17/1906	2140Z	33.3N	79.2W	80kt	1	30nmi	---	977mb	1018mb	SC1,NC1
6-9/27/1906	1100Z	30.2N	88.6W	95kt	2	43nmi	14'%	958mb	1013mb	MS2,AL2,AFL2,LA1
8-10/18/1906	0930Z	24.7N	81.1W	95kt	2	16nmi	---	967mb	1010mb	BFL2,CFL2
8-10/18/1906	1130Z	25.2N	80.8W	95kt	2	16nmi	---	967mb	1010mb	CFL2,BFL1
2-5/29/1908&	2100Z	35.2N	75.6W	55kt	TS	---	---	989mb	1015mb	(None)
3-7/31/1908	1130Z	34.6N	77.1W	70kt	1	---	---	(985mb)	1017mb	NC1
2-6/29/1909	1700Z	26.1N	97.2W	85kt	2	---	7'%	972mb	1012mb	ATX2
4-7/21/1909	1650Z	28.9N	95.3W	100kt	3	19nmi	10'%	959mb	1015mb	CTX3
6-8/27/1909#	2140Z	23.7N	97.7W	65kt	1	---	---	(955mb)	1014mb	ATX1
8-9/21/1909	0000Z	29.5N	91.3W	105kt	3	28nmi	15'%	952mb	1012mb	LA3,MS2

10-10/11/1909&	1800Z	24.7N	81.0W	90kt	2	22nmi	---	957mb	1009mb	BFL2,CFL2
3-9/14/1910	2200Z	26.9N	97.4W	95kt	2	---	---	(965mb)	1011mb	ATX2
5-10/17/1910*	1900Z	24.6N	82.6W	90kt	2	28nmi	---	941mb	1008mb	BFL2
5-10/18/1910	0600Z	26.5N	82.0W	95kt	2	28nmi	15'%	955mb	1008mb	BFL2

Notes:

Date/Time: Day and time when the circulation center crossed the U.S. coastline (including barrier islands). Time was estimate to the nearest hour for the period of 1851 to 1899 and to the nearest ten minutes for the period of 1900 to 1910.

Lat/Lon: Location was estimated to the nearest 0.1 degrees latitude and longitude (about 6 nmi).

Max Winds: Estimated maximum sustained 1-min surface (10 m) winds to occur along the U. S. coast. Winds are estimated to the nearest 10 kt for the period of 1851 to 1885 and to the nearest 5 kt for the period of 1886 to 1910.

Saffir-Simpson: The estimated Saffir-Simpson Hurricane Scale at landfall based upon maximum sustained surface winds. "TS" indicates that the hurricane's center made landfall, but that hurricane force wind remained offshore.

RMW: The radius of maximum winds at the surface (primarily for the right front quadrant of the hurricane), if available.

Storm surge: Maximum observed storm surge, if available. Though a higher value may have occurred, it might not have been recorded.

Central Pressure: The observed (or analyzed from peripheral pressure measurements) minimum central pressure of the hurricane at landfall. Central pressure values in parentheses indicate that the value was a simple estimation (based upon a wind-pressure relationship) and not directly observed or calculated.

Environmental Pressure: The sea level pressure at the outer limits of the hurricane circulation determined by moving outward from the storm center to the first anticyclonically turning isobar in four equally spaced directions and averaging the four pressures thus obtained.

States Affected: The impact of the hurricane on individual U.S. states based upon the Saffir-Simpson Scale (again through the estimate of the maximum sustained surface winds at each state). (ATX-South Texas, BTX-Central Texas, CTX-North Texas, LA-Louisiana, MS-Mississippi, AL-Alabama, AFL-Northwest Florida, BFL-Southwest Florida, CFL-Southeast Florida, DFL-Northeast Florida, GA-Georgia, SC-South Carolina, NC-North Carolina, VA-Virginia, MD-Maryland, DE-Delaware, NJ-New Jersey, NY-New York, PA-Pennsylvania, CT-Connecticut, RI-Rhode Island, MA-Massachusetts, NH-New Hampshire, ME-Maine. In Texas, south refers to the area from the Mexican border to Corpus Christi; central spans from north of Corpus Christi to Matagorda Bay and north refers to the region from north of Matagorda Bay to the Louisiana border. In Florida, the north-south dividing line is from Cape Canaveral [28.45N] to Tarpon Springs [28.17N]. The dividing line between west-east Florida goes from 82.69W at the north Florida border with Georgia, to Lake Okechobee and due south along longitude 80.85W.)

$ - Indicates that the hurricane may not have been reliably estimated for intensity (both central pressure and maximum sustained wind speed) because of landfall in a relatively uninhabited region. Errors in intensity are likely to be underestimates of the true intensity.

* - Indicates that the hurricane center did not make a U.S. landfall, but did produce hurricane force winds over land. The position indicated is the point of closest approach. In this table, maximum winds refer to the strongest winds estimated to impact the United States. In this case, central pressure is given for the hurricane's point of closest approach.

& - Indicates that the hurricane center did make a direct landfall, but that the strongest winds likely remained offshore. Thus the winds indicated here are lower than in HURDAT.

- Indicates that the hurricane made landfall over Mexico, but also caused hurricane winds in Texas. The position given is that of the Mexican landfall. The strongest winds at landfall impacted Mexico, while the weaker maximum sustained winds indicated here were conditions estimated to occur in Texas. Indicated central pressure given is that at Mexican landfall.

% - Indicates that the value listed is a "storm tide" observation rather than a "storm surge", which removes the astronomical tide component.

Table 9: Continental United States Tropical Storms: 1851-1910

#/Date	Time	Lat	Lon	Max Winds	Landfall State
6-10/19/1851	1500Z	41.1N	71.7W	50kt	NY
3- 8/19/1856	1100Z	34.8	76.4	50	NC
4- 9/30/1857$	1000Z	25.8	97.0	50	TX
3- 9/14/1858$	1500Z	27.6	82.7	60	FL
3- 9/16/1858*	0300Z	35.2	75.2	50	NC
7-10/17/1859$	1600Z	26.4	80.1	60	FL
7-10/ 7/1861	1200Z	35.3	75.3	50	NC
8-11/ 1/1861$	0800Z	26.0	81.8	60	FL
8-11/ 3/1861	0800Z	41.0	72.3	60	NY
8-11/ 3/1861	0900Z	41.2	72.0	50	CT
6- 9/18/1863	1300Z	34.6	77.1	60	NC
9- 9/29/1863$	1200Z	29.3	94.8	60	TX
2- 6/30/1865$	1800Z	26.0	97.5	50	TX
3- 8/22/1865*	1800Z	34.5	74.6	40	NC
6- 9/ 7/1865$	0000Z	29.7	92.0	60	LA
7-10/30/1866	0800Z	39.5	74.3	60	NJ
2- 8/ 2/1867*	0300Z	35.3	74.7	60	NC
2- 8/ 2/1867*	2200Z	40.7	69.6	50	MA
2-10/ 4/1868$	1600Z	29.9	85.4	60	FL
2- 9/ 3/1870*	1800Z	40.5	68.8	40	MA
1- 6/ 4/1871	0700Z	29.1	95.1	50	TX
2- 6/ 9/1871	1700Z	29.2	95.0	50	TX
3-8/23/1871	0000Z	31.2	81.3	60	GA
7-10/ 5/1871$	1600Z	30.0	83.9	60	FL
1- 7/11/1872	0500Z	29.1	89.1	50	LA
1- 7/11/1872	0800Z	30.2	89.0	50	MS
5-10/23/1872$	0800Z	27.9	82.7	50	FL
5-10/25/1872	0100Z	34.4	77.7	50	NC
1- 6/ 2/1873	1100Z	30.8	81.4	40	GA
4- 9/23/1873$	1000Z	27.8	82.8	50	FL
1- 7/ 4/1874	2000Z	28.5	96.2	50	TX
4- 9/ 4/1874$#	1200Z	25.0	97.6	40	TX
4- 9/27/1875$	1300Z	30.1	85.7	50	FL
2- 9/16/1876$*	1500Z	25.5	79.7	40	FL
7-10/26/1877$	2100Z	29.3	83.2	40	FL
1- 7/ 2/1878$	1500Z	26.0	81.8	40	FL
5- 9/ 7/1878$	2100Z	24.7	80.9	60	FL
5- 9/ 8/1878$	0200Z	25.2	81.0	60	FL
8-10/10/1878$	2100Z	29.9	85.4	50	FL
11-10/22/1878$*	0000Z	25.9	79.8	50	FL
2-8/19/1879&	0600Z	41.4	70.8	60	MA
5-10/ 7/1879	0500Z	29.0	89.2	50	LA
6-10/16/1879$	0800Z	30.4	86.6	50	FL
7-10/27/1879$	2100Z	29.0	82.7	60	FL
1- 6/24/1880	1500Z	28.7	95.7	40	TX
6- 9/ 8/1880	1600Z	29.8	83.6	50	FL
11-10/23/1880	0800Z	41.3	70.0	60	MA
11-10/23/1880	1300Z	44.0	68.8	60	ME
1- 8/ 3/1881	1300Z	30.2	88.3	50	AL
2- 8/13/1881	2100Z	28.0	96.9	40	TX
4- 9/22/1882	2200Z	34.7	77.0	50	NC
4- 9/24/1882	0500Z	40.7	72.8	40	NY

3- 9/11/1884	0100Z	31.6	81.2	40	GA
3- 8/22/1885	2300Z	30.1	85.7	50	FL
4- 9/21/1885	0300Z	29.0	89.4	50	LA
4- 9/21/1885	1200Z	30.0	85.6	50	FL
4- 9/23/1885*	0300Z	41.6	69.7	50	MA
6- 9/26/1885	0400Z	29.6	89.0	60	LA
6-10/ 2/1885*	1500Z	35.0	74.8	50	NC
8-10/11/1885	2200Z	29.4	83.2	60	FL
5-8/18/1886*$	0100Z	23.9	81.9	55	FL
3-6/14/1887	0700Z	30.2	88.7	35	MS
7-8/25/1887*	0600Z	35.0	74.4	50	NC
16-10/30/1887$	0100Z	26.8	82.3	40	FL
2-7/5/1888	1600Z	28.8	95.6	50	TX
4-9/6/1888*$	0000Z	23.0	81.9	50	FL
5-9/8/1888$	0000Z	26.7	80.0	45	FL
6-9/26/1888&	1300Z	41.6	69.9	55	MA
7-10/11/1888	1600Z	33.9	78.1	60	NC
9-11/25/1888*	1800Z	35.3	74.2	60	NC
2-6/17/1889	1500Z	29.1	82.9	45	FL
4-9/11/1889*	2100Z	38.4	72.7	60	NJ
6-9/23/1889	1300Z	30.3	87.7	60	FL
9-10/5/1889$	2300Z	24.7	81.1	40	FL
9-10/6/1889$	0100Z	25.2	80.9	40	FL
2-8/27/1890	1600Z	29.1	90.8	50	LA
7-10/9/1891$	1400Z	25.8	81.7	45	FL
1-6/10/1892$	2300Z	25.7	81.3	40	FL
4-9/12/1892	0700Z	29.0	90.6	50	LA
9-10/24/1892$	1900Z	27.6	82.8	45	FL
1-6/15/1893	2300Z	29.9	83.7	60	FL
11-10/23/1893	0300Z	35.2	75.6	50	NC
11-10/23/1893	1100Z	38.1	75.6	45	VI
12-11/8/1893*	1800Z	35.6	74.6	55	NC
2-8/7/1894	1800Z	30.3	87.6	50	AL
4-9/28/1894	1200Z	34.7	76.7	60	NC
1-8/15/1895	1900Z	29.3	89.6	50	LA
1-8/16/1895	1300Z	30.2	88.8	45	MS
4-10/7/1895	0400Z	29.3	94.8	35	TX
6-10/16/1895$	1300Z	25.7	81.3	35	FL
5-10/9/1896$	0200Z	26.4	82.0	50	FL
5-10/13/1896*	1200Z	40.7	67.2	60	RI
2-9/10/1897$&	1800Z	24.4	81.9	50	FL
3-9/21/1897$	0200Z	26.7	82.3	60	FL
3-9/23/1897&	1000Z	35.2	75.7	50	NC
3-9/24/1897	1100Z	40.8	72.7	50	NY
3-9/24/1897	1300Z	41.3	72.2	45	CT
5-10/20/1897	2000Z	35.2	75.5	55	NC
6-10/25/1897	2300Z	36.1	75.8	55	NC
1-8/2/1898$	0300Z	27.1	80.1	35	FL
5-9/20/1898	1100Z	29.6	92.8	50	LA
6-9/28/1898	0700Z	29.4	94.7	50	TX
8-9/26/1898$	0600Z	25.1	80.8	40	FL
9-10/11/1898$&	1200Z	24.5	80.0	40	FL
1-6/27/1899	0900Z	29.1	95.1	35	TX
2-7/30/1899$	1000Z	24.9	80.6	40	FL
3-8/13/1899*	1200Z	27.0	78.6	60	FL
6-10/5/1899$	1000Z	27.9	82.8	50	FL
3-9/13/1900	0630Z	29.2	89.5	40	LA

3-9/13/1900	1500Z	30.3	88.8	35	MS
6-10/12/1900	0250Z	29.5	83.3	40	FL
1-6/13/1901	2050Z	29.9	84.6	35	FL
2-7/10/1901	1010Z	28.6	96.0	45	TX
3-7/12/1901	2210Z	34.0	77.9	35	NC
4-8/10/1901	2130Z	26.3	80.1	40	FL
7-9/17/1901	1930Z	30.4	86.6	50	FL
9-9/28/1901	0250Z	29.9	84.6	40	FL
1-6/14/1902	2310Z	29.8	83.7	50	FL
2-6/26/1902	2110Z	27.7	97.2	60	TX
4-10/10/1902	2120Z	30.3	87.3	50	FL
3-10/20/1904	1010Z	25.5	81.2	35	FL
5-11/3/1904	1230Z	30.5	86.4	35	FL
3-9/29/1905	0940Z	29.6	92.6	45	LA
5-10/9/1905	1720Z	29.5	91.4	45	LA
1-6/12/1906	2030Z	30.1	85.6	45	FL
8-10/21/1906	0840Z	30.2	81.4	50	FL
1-6/28/1907	2340Z	30.3	85.9	50	FL
2-9/21/1907	1430Z	30.2	89.0	40	MS
3-9/28/1907	2020Z	30.1	85.7	45	FL
2-5/29/1908&	2100Z	35.2	75.6	55	NC
2-5/30/1908	2250Z	41.3	72.0	35	CT
4-9/1/1908	0900Z	34.7	76.5	45	NC
3-6/28/1909	2010Z	26.0	80.1	45	FL
3-6/30/1909	1400Z	30.1	84.1	35	FL
7-8/29/1909	0900Z	26.4	80.1	45	FL
2-8/21/1910#	0000Z	25.7	97.2	40	TX

Notes:

Date/Time: Day and time when the circulation center crossed the U.S. coastline (including barrier islands). Time was estimated to the nearest hour for the period of 1851 to 1899 and to the nearest ten minutes for the period of 1900 to 1910.

Lat/Lon: Location was estimated to the nearest 0.1 degrees latitude and longitude (about 6 nmi).

Max Winds: Estimated maximum sustained 1-min surface (10 m) winds to occur along the U. S. coast. Winds are estimated to the nearest 10 kt for the period of 1851 to 1885 and to the nearest 5 kt for the period of 1886 to 1910.

Landfall States: TX- Texas, LA-Louisiana, MS-Mississippi, AL-Alabama, FL- Florida, GA-Georgia, SC-South Carolina, NC-North Carolina, VA-Virginia, MD-Maryland, DE-Delaware, NJ-New Jersey, NY-New York, CT-Connecticut, RI-Rhode Island, MA-Massachusetts, NH-New Hampshire, ME-Maine.

$ - Indicates that the tropical storm may not have been reliably estimated for intensity (maximum sustained wind speed) because of landfall in a relatively uninhabited region. Errors in intensity are likely to be underestimates of the true intensity.

- Indicates that the tropical storm or hurricane made landfall over Mexico, but also caused tropical storm force winds in Texas. The position given is that of the Mexican landfall. The strongest winds at landfall impacted Mexico, while the weaker maximum sustained winds indicated here were conditions estimated to occur in Texas.

* - Indicates that the tropical storm or hurricane center did not make a U.S. landfall, but did produce tropical storm force winds over land. The position indicated is the point of closest approach. In this table, maximum winds refer to the strongest winds estimated to impact the United States.

& - Indicates that the tropical storm or hurricane center did make a direct landfall, but that the strongest winds likely remained offshore. Thus the winds indicated here are lower than in HURDAT.

Table 10: Estimated dates when accurate tropical cyclone records began for specified regions of the United States based upon U.S Census reports and other historical analyses. Years in parenthesis indicate possible starting dates for reliable records before the 1850s that may be available with additional research.

State	Date
Texas - south	1880
Texas - central	1850
Texas - north	1860
Louisiana	1880
Mississippi	1850
Alabama	< 1851 (1830)
Florida – northwest	1880
Florida – southwest	1900
Florida – southeast	1900
Florida – northeast	1880
Georgia	< 1851 (1800)
South Carolina	< 1851 (1760)
North Carolina	< 1851 (1760)
Virginia	< 1851 (1700)
Maryland	< 1851 (1760)
Delaware	< 1851 (1700)
New Jersey	< 1851 (1760)
New York	< 1851 (1700)
Connecticut	< 1851 (1660)
Rhode Island	< 1851 (1760)
Massachusetts	< 1851 (1660)
New Hampshire	< 1851 (1660)
Maine	< 1851 (1790)